OPERATIONAL ASPECTS OF THE RF CONTROL SYSTEM FOR THE TESLA TEST FACILITY

S.N. Simrock, K. Rehlich, T. Schilcher, DESY

1 ABSTRACT

The operation of multiple high gradient srf cavities driven by a single klystron is a challenging task. This is due to severe Lorentz force detuning, microphonics, power limitations, and parameter variations. Simulation results of power requirements with realistic distributions of loaded Q, Lorentz force detuning constant, mechanical time constant of the cavity, phase and amplitude of incident wave, and phase and gradient errors for vector sum are given. The microphonics modulate the detuning at the beginning of the pulse and thereby increase the power requirements. The algorithm for tuner control is based on detuning angle information during each pulse. The fully digital rf control system assists the operator in the calibration of the vector sum, optimization of feedback gains, and generation of feed forward tables. The goal is to minimize the power needed for control but also to maximize performance and robustness of the system. Extensive diagnostics allows one to study the performance of individual cavities. Issues such as operation of cavities at different gradients, and by-passing cavities are also discussed

2 INTRODUCTION

A complex system such as the rf control for the TESLA Test Facility requires sophisticated procedures for turn on, operation, and troubleshooting of the rf system. While it is planned to automate most of the procedures, it is still necessary that the operator be allowed to control the system manually comparable to an airline pilot who will usually activate the autopilot during flight while assuming full control during take-off and landing and if any problem occurs.

The parameters to be controlled are the time-varying feed forward tables, the time-varying feedback gain tables, the time-varying (during cavity filling) setpoint tables which include gradient and phase setpoint, the loop phase shifter, and the frequency tuners. Other parameters which may need adjustment are the calibration coefficients for cavity gradient and phase, the loaded Q, and the phase of the incident wave using a three stub waveguide tuner.

3 RF SYSTEM OPERATION

Operation of the RF system with 16 cavities driven by one klystron can be divided into several sections:

- Turn on with feed forward only and simulated beam. Raise gradient slowly. Optimize the pre-detuning.
- Application of feedback. Adjust loop phase shifter. Increase gain to nominal.
- Adjust feed forward and setpoint tables for optimum cavity filling. Minimize average (over many pulses) power for filling.
- Optimize feedback parameters for minimum residual amplitude and phase fluctuation during flat-top.
- Turn on beam. Start with short pulses, phase cavities, and increase pulse length. Feed forward tables must change according to beam structure.
- Adjust frequency tuner for minimum control power during beam on time.
- Activate adaptive adjustment of feed forward tables for minimum feedback effort.

3.1 Turn On Procedures (No Beam)

Load feed forward tables for low gradient operation. Typically values are 10 kW of forward power per cavity (for 5 MV/m operation) for the first 500 µs and 2.5 kW for the following 800 µs. The phase of the incident wave is initially constant. Adjust frequency tuners for an average pre-detuning which result in a flat-top at nominal gradient (230 Hz for 25 MV/m). The pre-detuning is determined from the slope of the time dependency of the cavity phase during field decay. The detuning during field decay is given by

$$\Delta\omega = \omega_0 - \omega_{rf} = \frac{d\phi}{dt} .$$

The effect of Lorentz force detuning is small due to the low gradient of approximately 5 MV/m, however, averaging over microphonics is necessary. The slope of $\phi_{cav}(t)$ will be almost constant during the first few hundred µs of the decay since the dominant microphonic noise contributions are around 27 Hz. The pulse to pulse variations in detuning are a direct measure of the microphonic noise amplitude.

Higher gradients are reached by scaling the feed forward tables. When the nominal gradient is reached (200 kW of forward power for filling and 50 kW for flat-top are required for a gradient of 25 MV/m), the gradients in the individual cavities should display a flat-top (flatness better than 10%), and the field vectors should line up with approximately the same phase.

There are several possibilities why the observed pulse may not be flat:

- Incident power is not consistent with the desired gradient. In this case the pre-detuning doesn't match the operating conditions. Correct power level.
- Pre-detuning is incorrect. It may have drifted while performing the turn on procedure. Verify the de-tuning during the decay of the cavity field. Correct tuner position.
- The loaded Q of the cavity is incorrect. The design for 25 MV/m operation is $Q_L = 3 \cdot 10^6$. Correct loaded Q by adjustment of the fundamental coupler or with the three stub waveguide tuners.

Also if the cavity field vectors do not line up, there may be several causes:

- The coefficients for phase offsets are missing or incorrect. Download correct coefficients or calibrate vector-sum.
- The phases of the incident waves to each cavity are different from cavity to cavity. Adjust three stub waveguide tuners.
- The pre-detuning of various cavities is incorrect. In this case the vectors should have a common orientation at the beginning of the pulse.

Feedback can be added once the open loop response is close to the desired closed loop response. The initial setpoint table should include exponential filling of the cavity and constant phase. The loop phase shifter should be adjusted such that the tangent to the phase of the vector-sum at the beginning of the pulse agrees with the phase of the incident wave. Once the loop phase shifter is adjusted correctly, the feedback gain should be increased from zero to the required gain (=50). Once a well regulated flat-top is achieved, the incident power should appear as shown in Figure 1.

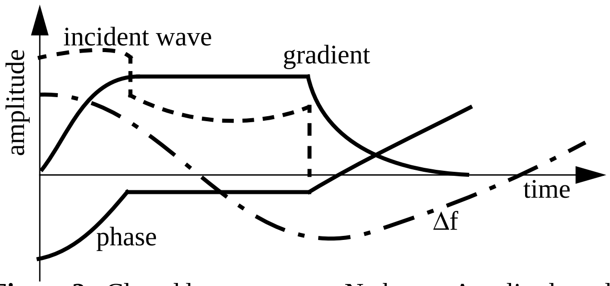

Figure 2 : Closed loop response. No beam. Amplitude and phase are constant during beam acceleration. The forward power is time dependent due to time varying cavity detuning.

The additional power required for filling is due to the pre-detuning of the cavity. With properly adjusted feed forward and setpoint tables during the cavity filling, the power curve should approach a flat line since the generator is now following the resonance frequency on average during the filling time of the cavity.

The minimum of the power curve during the flat-top should be about in the middle to minimize the peak power requirements.

During the last step of the turn on, beam will be added. Starting with short beam pulses of 10 μs duration, the cavity phase is adjusted for maximum acceleration. This can be accomplished by phasing the cavity for maximum beam induced transient, or calibration of the zero crossing (higher accuracy since nulling method, no transient !) and subsequent adjustment of the cavity phase by 90 degrees.

When lengthening the beam pulses, the feed forward tables must be adjusted accordingly. The same is true for all other adjustments such as gradient and phase setpoint tables.

3.2 Fine Adjustment of Feedback Parameters

The main purpose of the feed forward algorithm is to reduce the workload for the feedback. Repetitive errors as a result of the Lorentz force detuning can be compensated by feed forward. Perturbations of a statistical nature such as microphonics, must be compensated by feedback.

The feed forward tables are adjusted such that the average control effort of the feedback loop is minimized. Since all control information is available within the digital feedback system, it is just a matter of adding the average control action of the feedback algorithm to the feed forward table. This can be done periodically to correct for slow drifts of parameters such as average pre-detuning, microphonic noise levels, and beam current. This process is fully automated since it requires the update of 2048x2 coefficients.

The feedback is adjusted for minimum residual amplitude and phase errors. Excessive gain will induce significant noise (phase noise from master oscillator is the dominating source) in the incident wave and may therefore increase residual noise. High gains could also result in instabilities in the feedback loop. A state estimator is used to determine the actual cavity field fluctuation since the resolution of the measured signal is dominated by phase noise of the frequency reference.

3.3 Minimizing Control Power

Power is minimized during filling and flat-top. First the power during flat-top must be minimized. This is accomplished by adjusting the frequency tuner. The goal is to set the pre-detuning such that the cavity resonance frequency and the operating frequency agree in the middle of the beam pulse. From the numerical model, this can be related to the detuning at the end of the beam pulse if the gradient follows the predicted flat-top curve closely. The tuning angle at the beginning of the rf pulse is also measured and used for diagnostics. It is desirable to determine the resonance frequency of each cavity in the middle of the beam pulse, but this computation intensive algorithm has not yet been implemented.

Once the power requirement during the flat-top is minimized, it is possible to minimize the power required during filling. The goal here is to follow the average resonance frequency (averaged over microphonics and number of cavities) of the ensemble of 16 cavities. The time dependency of the phase of setpoint and feed forward table during filling is varied until the average power is minimized.

3.4 Control of Frequency Tuner

The frequency tuner can be operated in different modes:

- Maintain constant average detuning during the decay of the cavity field. Time constant of the average is a few hundred pulses. The tuner is activated when the average detuning exceeds 50 Hz and stopped when it is less than 10 Hz. Mechanical wearout of the tuner mechanism is minimized by implementation of hysteresis.
- Maintain a constant average phase between incident and transmitted wave (probe signal) in the middle of the beam pulse of each cavity. Same time constant and similar hysteresis as in the previous mode.
- Maintain flat-top in individual cavities. Algorithm to be developed.

Other functions include detuning of cavities to be bypassed by at least 100 bandwidth (20 kHz), and automated tuning if cavities are detuned by several bandwidth such that cavity signal is too weak for tuner activation. Cavity tuning is inhibited if the gradient is lower than 2 MV/m.

4 DIAGNOSTICS

4.1 Calibration Error of the Vector-Sum

The calibration of the vector-sum is described in detail in [1]. It is, however, important to diagnose control problems induced by errors in the vector-sum. Indications are inconsistencies between incident wave, beam induced transients, reflected power, and cavity tuning.

4.2 Gradient and Phase Calibration

Gradient and phase calibration errors are also identified by consistency check between various variables in the rf control system. The model accurately describes the relation between cavity gradient, cavity tuning, loaded Q of the cavity, generator power, and beam current and phase. At 25MV/m and a beam current of 8 mA, the forward power should be approximately 200 kW. The reflected power should be zero. The rf control system will issue a warning if the measured signals are inconsistent.

4.3 Quench Detection

A cavity quench is characterized by a fast drop in the accelerating gradient. The decay of the cavity field will be significantly faster than the time constant determined by the loaded Q of the cavity. In this case the forward power may also show a sharp rise. It will be necessary to lower the gradient which has to be done for all cavities simultaneously.

5 SPECIAL PROCEDURES

Special procedures are required when the rf system is not operated under nominal conditions such as a gradient of 15 MV/m and beam loading of 8 mA.

4.1 Operation at Different Gradients

It is desirable to operate cavities at different gradients to maximize the energy gain of a system with 16 cavities. The maximum operable gradient is limited by quench or field emission and can vary between 15 MV/m and 25 MV/m. Therefore various methods have been studied. The only installed available actuator to accomplish this are the frequency tuner, the three stub waveguide tuner, and the coupling adjustment of the fundamental coupler. Simulations have shown that a flat top at different gradients cannot be achieved by adjustment of pre-detuning and loaded Q. Proper choice of these parameters however permits that a cavity is operated at a lower gradient at the cost of large gradient fluctuations in these cavities during the beam pulse.

6 CONCLUSION

The control of multiple superconducting cavities driven by one klystron and operated at high gradients and with pulsed rf is feasible although challenging. Procedures for startup and operation have been developed based on experience with the operation of a single cavity. A model describing the dynamics of the cavity-rf-beam interaction has been developed and is routinely used to test the proposed procedures.

7 REFERENCES

[1] S. N. Simrock, T. Schilcher, DESY, *Transient Beam Loading Based Calibration of the Vector-Sum for the TESLA Test Facility*, these proceedings.